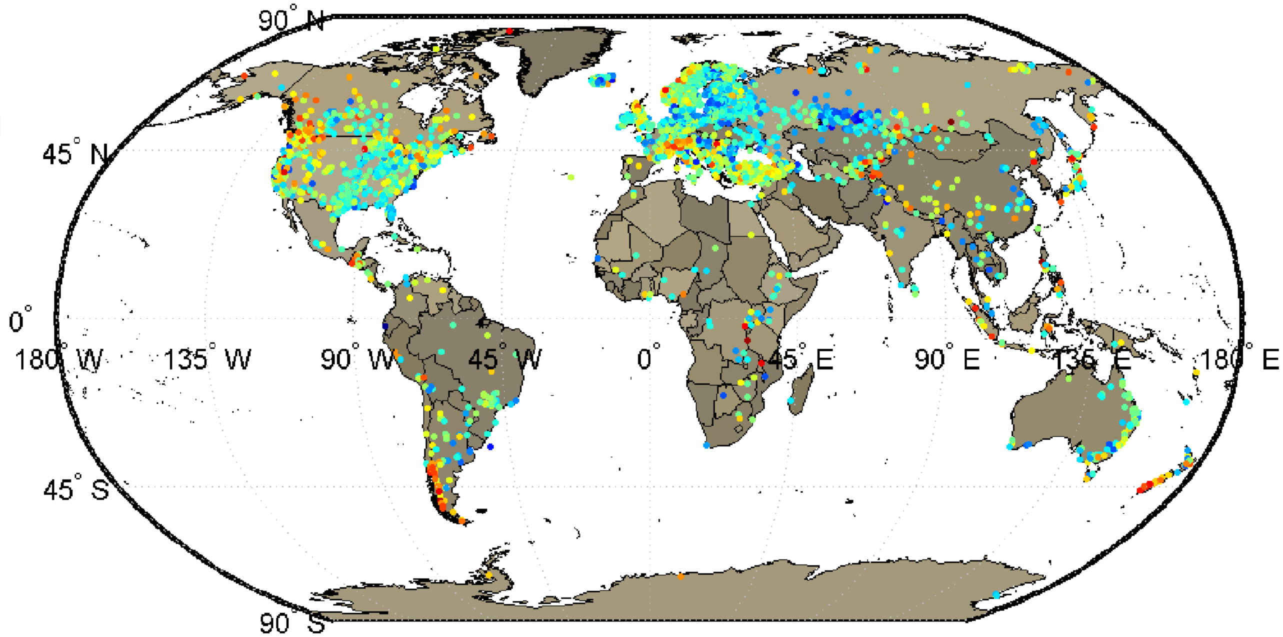
Leibniz-Institute of
Freshwater Ecology
and Inland Fisheries

Perspectives of zero-dimentional modeling for lake representation in climate models

Georgiy Kirillin and Tom Shatwell

5th workshop on parameterization of lakes in NWP and climate modeling

Motivation

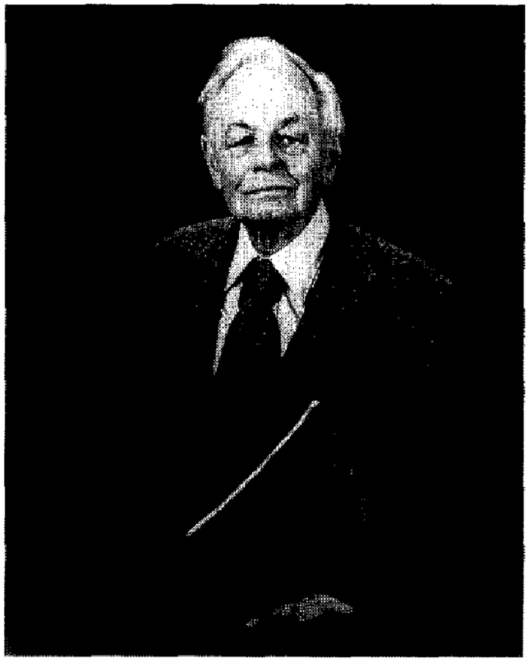


Lake depths from GLDB (After Kourzeneva et al. 2012, Choulga et al. 2014)

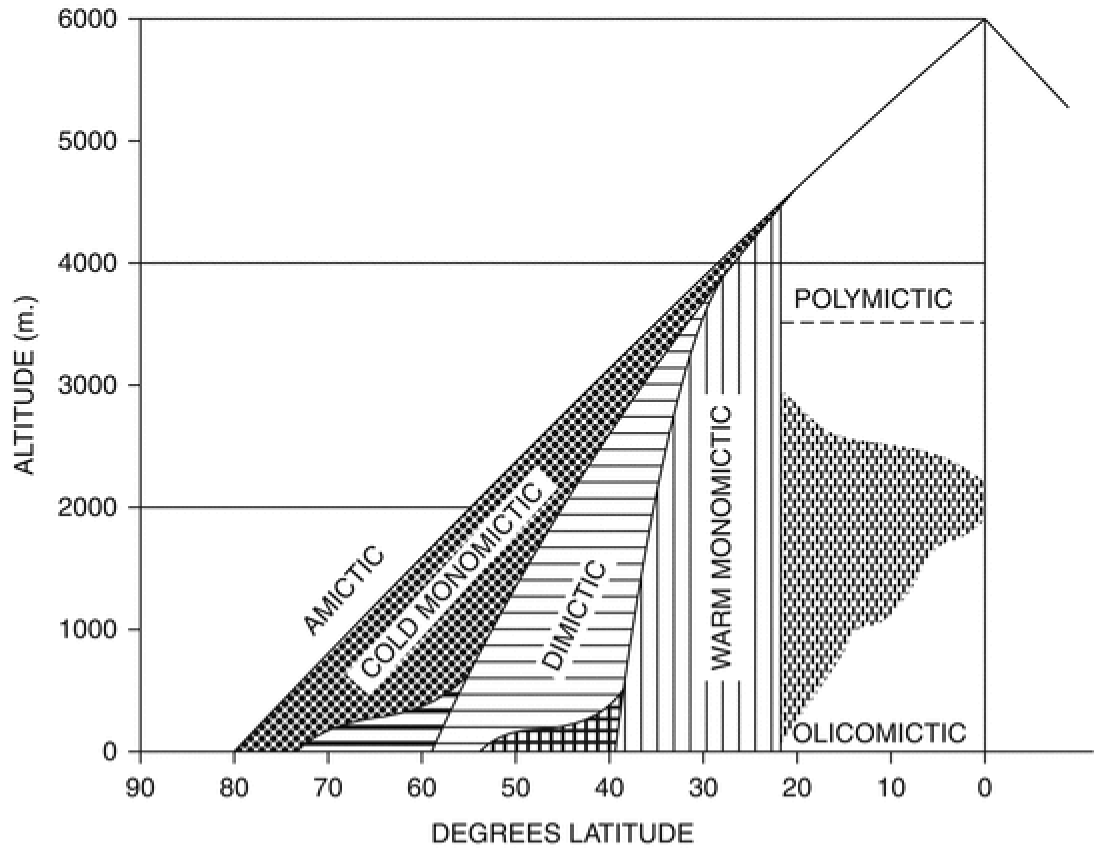
Do we need to model vertical thermal structure of all lakes?

Motivation

Hutchinson and Löffler, *PNAS 42*, 1956

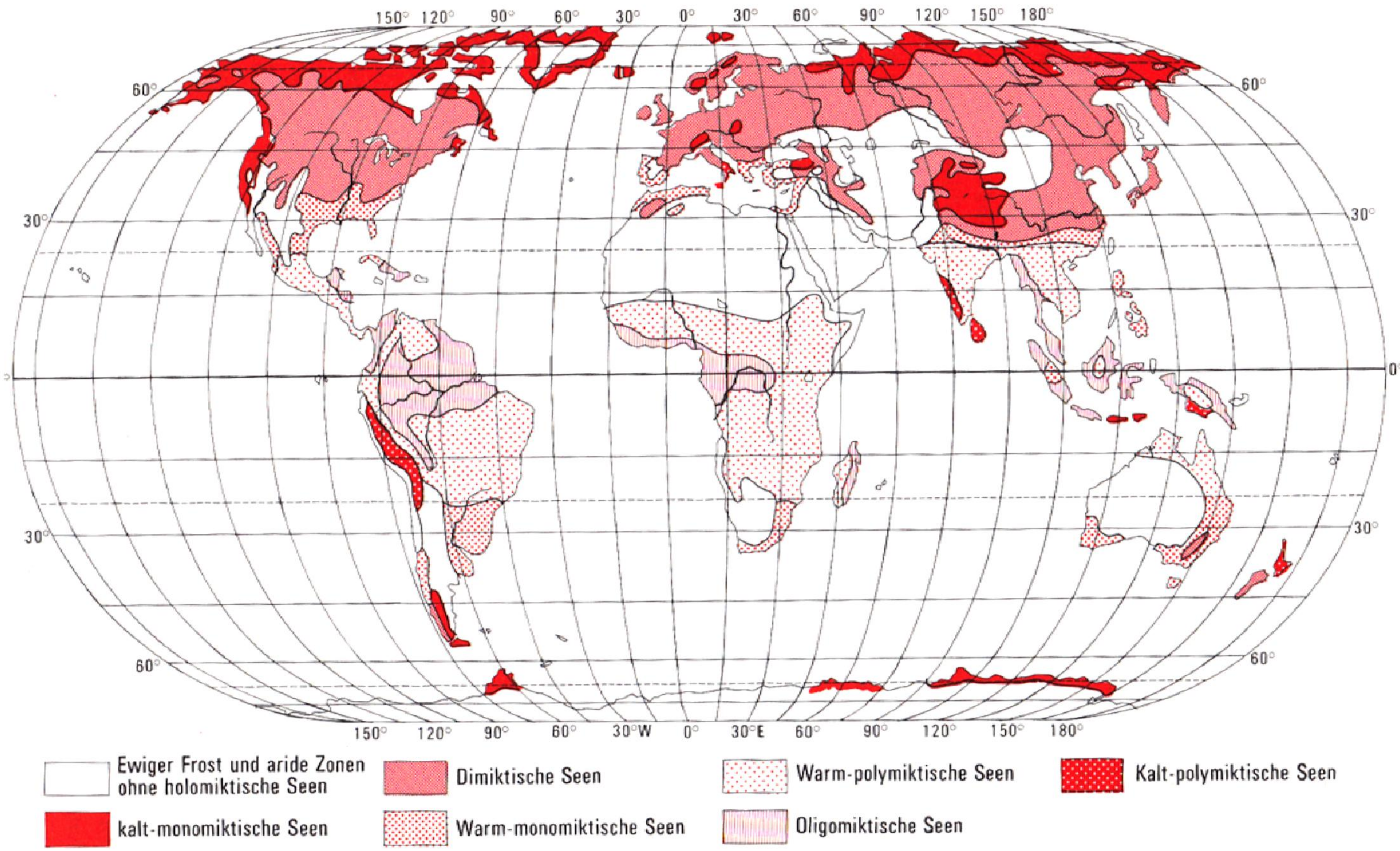


G. Evelyn Hutchinson
1903-1991
(from Slobodkin and Slack, *Endeavour 23,* 1999)

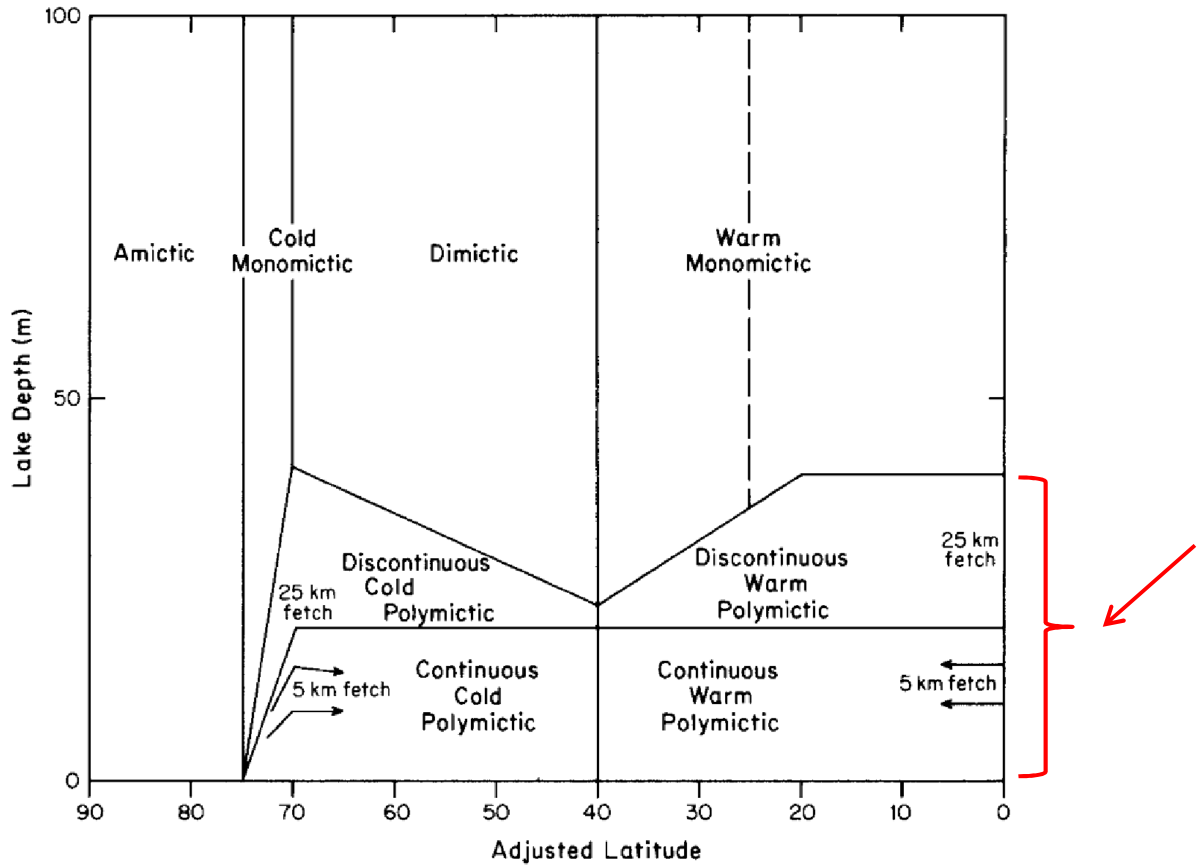


Seasonal mixing regime can be predicted from climatic conditions

Distribution of lakes according to Hutchinson & Löffler's model



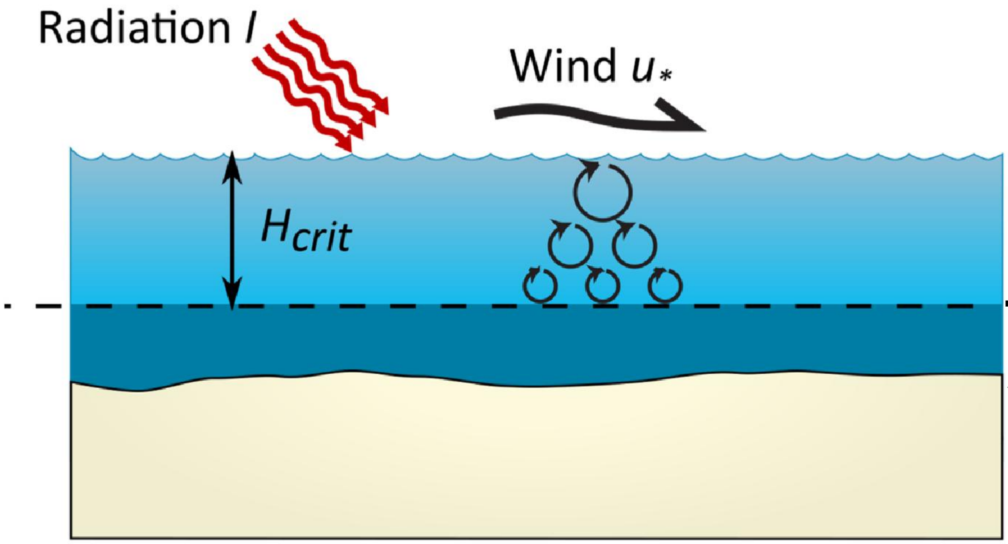
Extension of Hutchinson&Löffler's model by Lewis (*Can J Fish Aq Sci 40*, 1983)

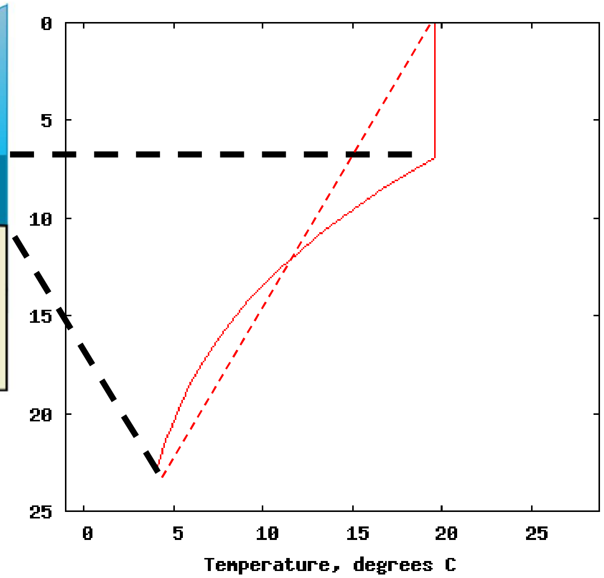


Lake depth is another important factor for seasonal mixing regime

An attempt to involve fetch into the game

Richardson Number





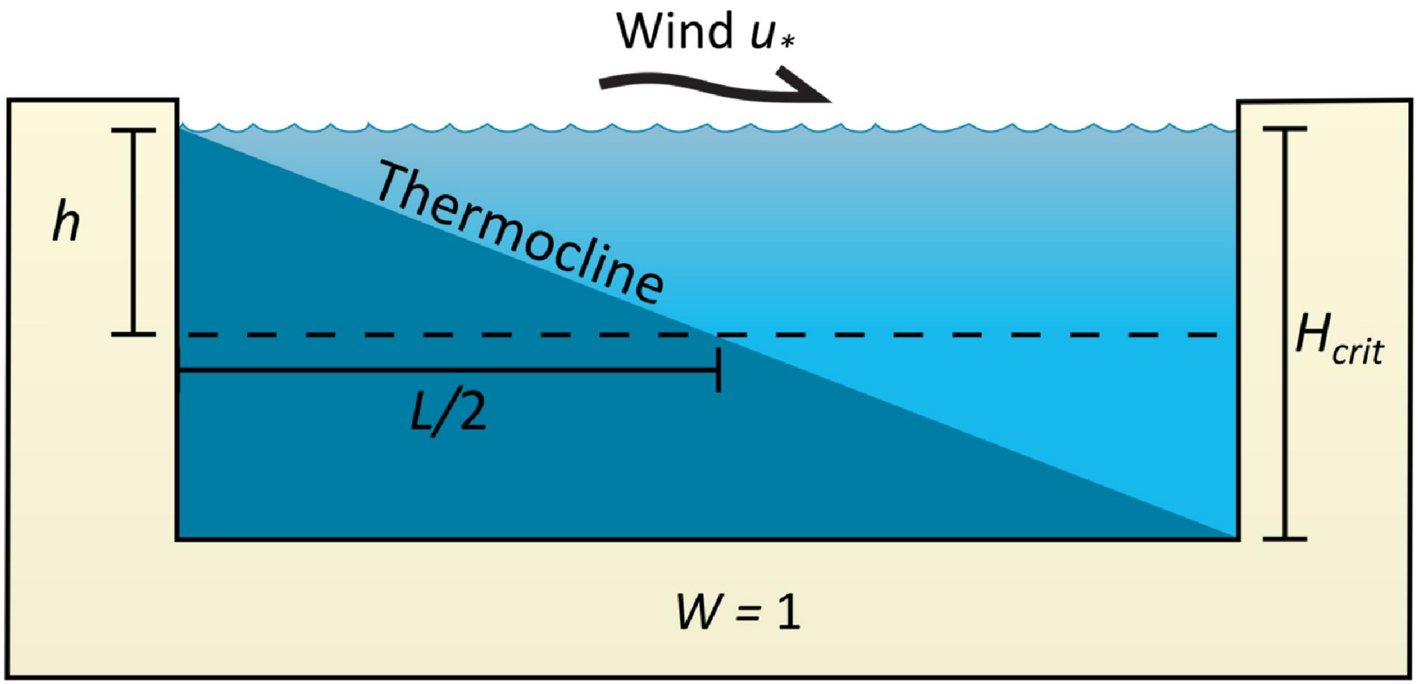
$$Ri = \frac{Buoyancy\ force}{Shear\ force}$$

$$\mathrm{Ri_g} = \left(-\partial b\, \partial z^{-1}\right)\left(\partial u\, \partial z^{-1}\right)^{-2} = N^2 S^{-2}$$

$$\mathrm{Rf} = B\, u_*{}^{-2}\, S^{-1}$$

$$\mathrm{Ri_{B*}} = \Delta b_0\, h\, u_*{}^{-2}$$

Wedderburn Number

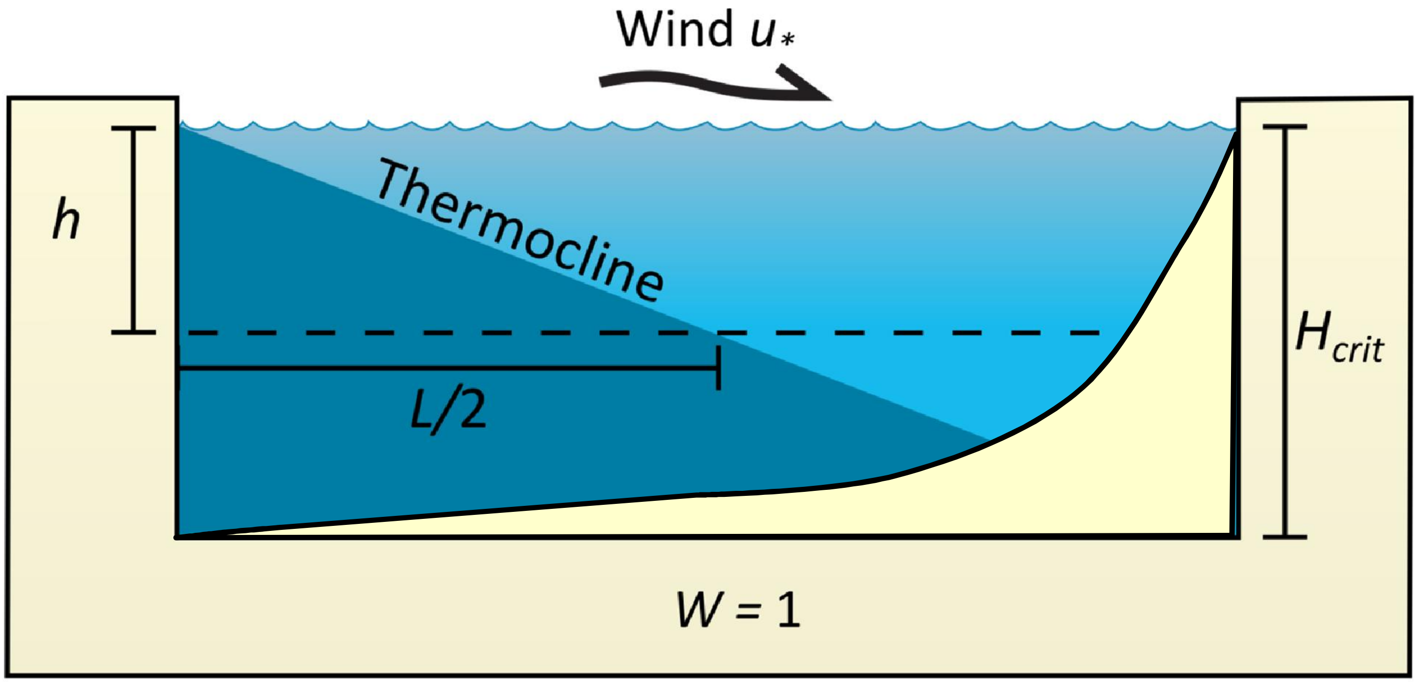


$$\mathrm{Ri}_{\mathrm{B}*} = \Delta b_0 \, h \, u_*^{-2}$$

$$W = \Delta b_0 \, h^2 \, u_*^{-2} (L/2)^{-1}$$

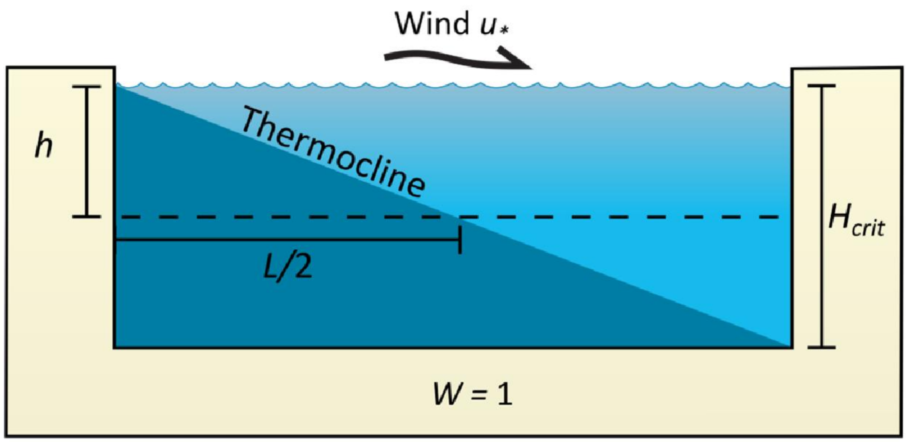
$$W = Ri_{\mathrm{B}*} A_{1/2}$$

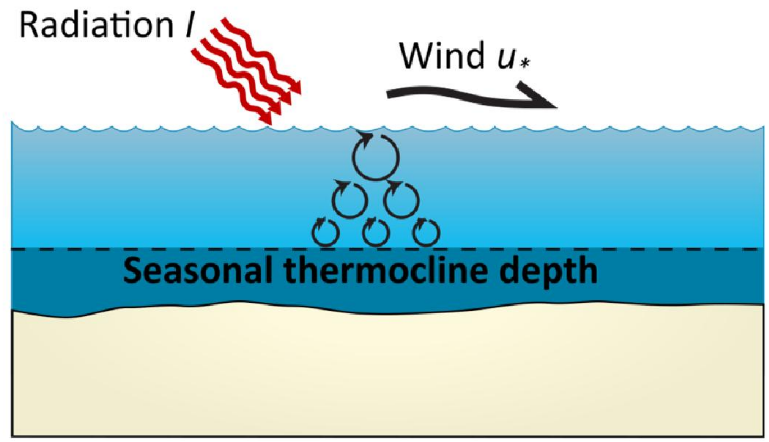
Lake Number



$$L_N = \mathrm{Ri}_s A_{1/2} = \frac{2St\, h}{L\, \rho_0\, u_*^2\, z_v}.$$

$$\mathrm{Ri}_s = St\, \left(\rho_0\, z_v\, u_*^2\right)^{-1}$$





$$W = Ri_{B*} A_{1/2}$$

W is based on *existing stratification* (bulk Ri).

To *predict* stratification we need a balance of external forces:

"*Seasonal Richardson Number*"

$$Ri = \frac{Buoyancy\ force}{Shear\ force}$$

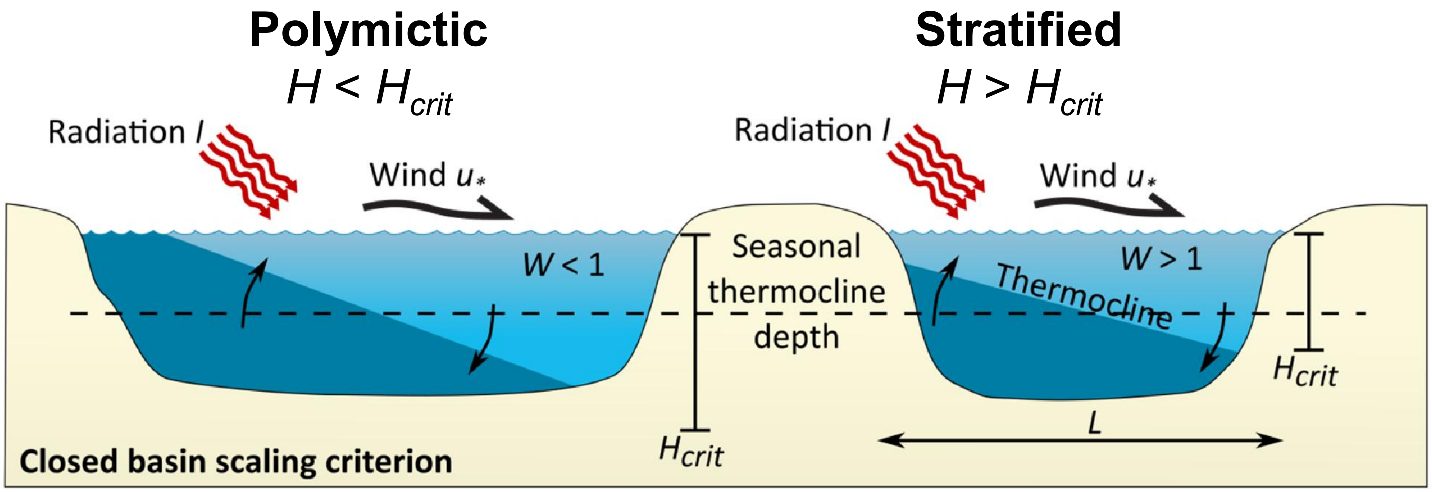
$$\mathrm{Rf} = B\,h\,u_*^{\ -3} = w_*^{\ 3} u_*^{\ -3} = h\,L_{MO}^{\ -1}$$

$$B_m = \frac{B_s + B_h}{2} + \frac{1}{2}\left(J_s + J_h - \frac{2}{h}\int_0^h J(z)dz\right)$$

$$J = g\alpha I \qquad L_{MO} = u_*^3\,(J_s)^{-1}$$

Further assumptions: $J(z) = J_s \exp(-\gamma z)$ $h_{SECCHI} \approx 2\gamma^{-1}$

Generalised scaling of stratification



- Scaling criterion estimates the critical lake depth (H_{crit}) so that the seasonal thermocline can tilt to the surface under mean forcing

Scaling criterion:

$$H_{crit} = C_1 h_{SECCHI} + \sqrt{C_1{}^2 h_{SECCHI}{}^2 + C_2 L L_{MO}}$$

Lake aspect ratio **Transparency** **Seasonal wind and radiation**

Asymptotic cases

KE budget
in the Mixed layer:

$$P - hB_m - h\varepsilon_m = 0 \qquad P = C_u u_*^3$$

$$C_u u_*^3 = \frac{J_s}{2}(C_{bs}h - h_{SECCHI})$$

$u_* >> 0, B_m > 0$

$$h = \sqrt{C_2 L L_{MO}}$$

According to Kitaigorodski (1960) $h \sim L_{MO}$

*The difference reflects the effect of the lateral dimensions **L** in lakes.*

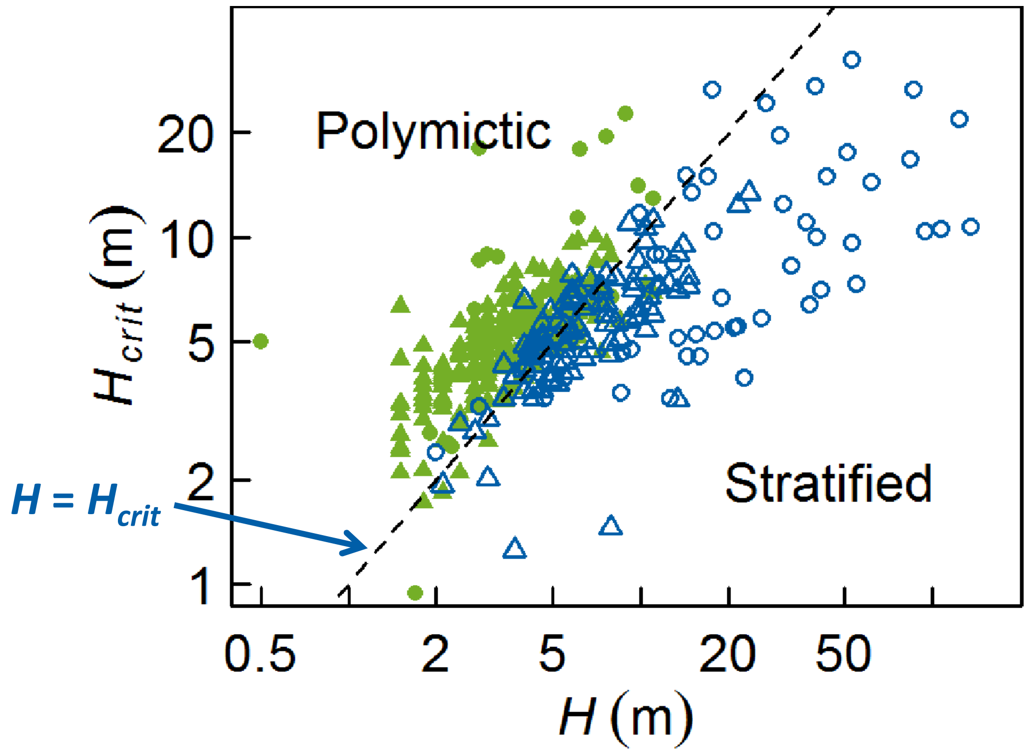
$u_* = 0, B_m < 0$

$h = h_{SECCHI}$

Identical to the result of Kraus and Rooth (1961)!

Validation of scaling criterion

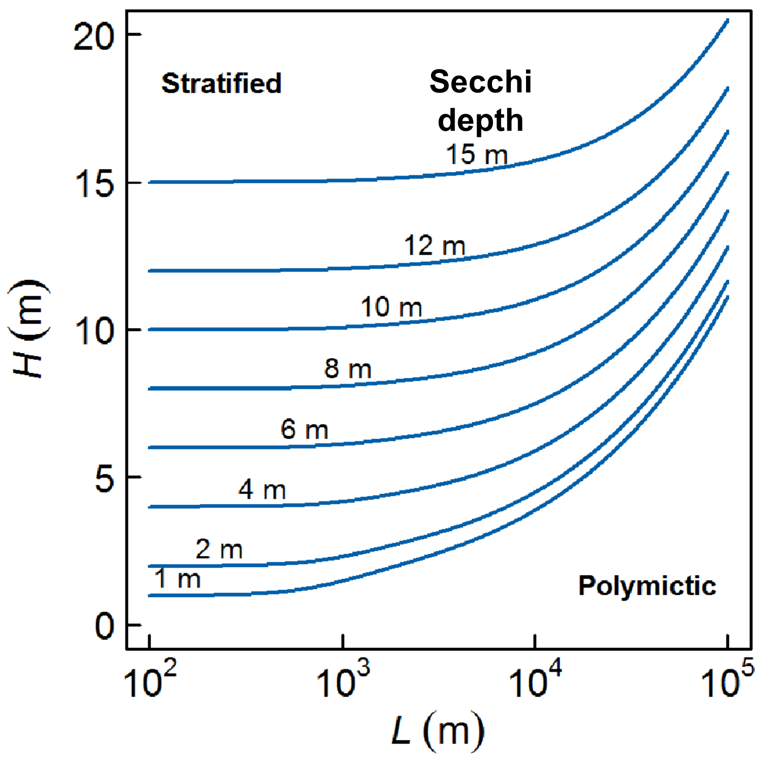
- Fitted to data set of world and American lakes (*n* = 375)
- Very good differentiation of mixing regime



$$H_{crit} = C_1 h_{SECCHI} + \sqrt{C_1{}^2 h_{SECCHI}{}^2 + C_2 L L_{MO}}$$

Fitted values: C_1 = 0.5, C_2 = 6*10^{-4} (0.6 m/km)

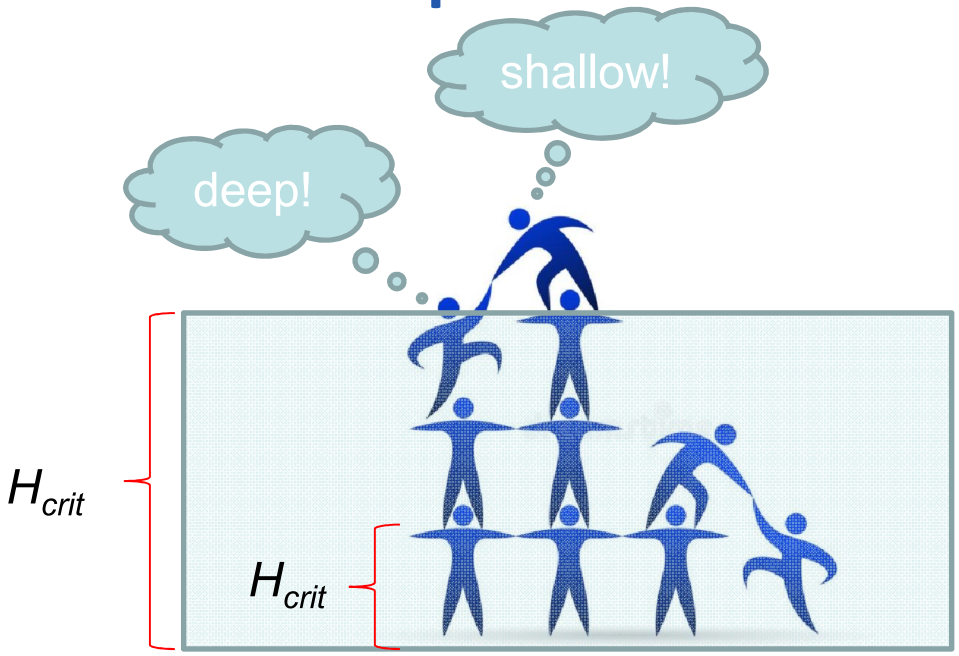
Effect of transparency and fetch on mixing regime



- In small lakes ($L < 1000$ m) mixing regime depends on transparency ($H_{crit} \approx h_{SECCHI}$)
- In large lakes, H_{crit} depends on LL_{MO}, especially wind

$$H_{crit} = C_1 h_{SECCHI} + \sqrt{C_1{}^2 h_{SECCHI}{}^2 + C_2 L L_{MO}}$$

Which lakes are deep?



Our short answer is:

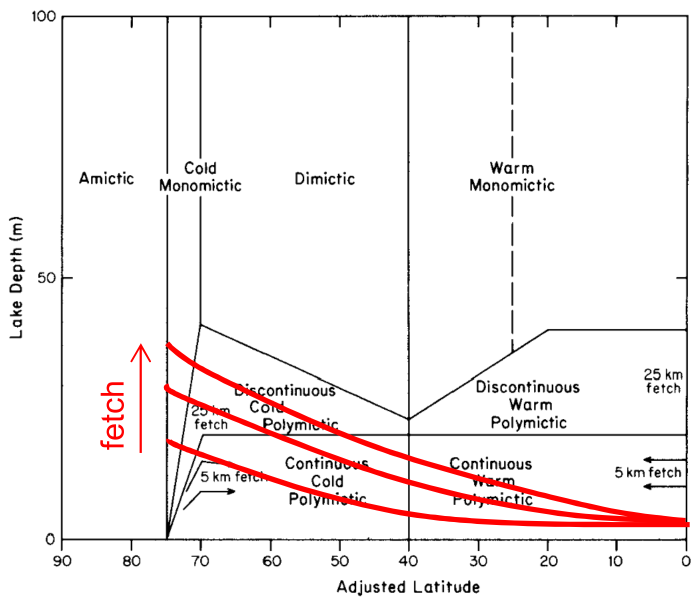
$$H_{crit} = C_1 h_{SECCHI} + \sqrt{C_1{}^2 h_{SECCHI}{}^2 + C_2 L L_{MO}}$$

What to do with this?

$$H_{crit} = C_1 h_{SECCHI} + \sqrt{{C_1}^2 {h_{SECCHI}}^2 + C_2 L L_{MO}}$$

Assuming L ~ 2 km, h_{SECCHI} = 2 m:

$$H_{crit} = 1 + (1 + L_{MO})^{1/2}$$



The world lake classification can be refined based on physical criteria

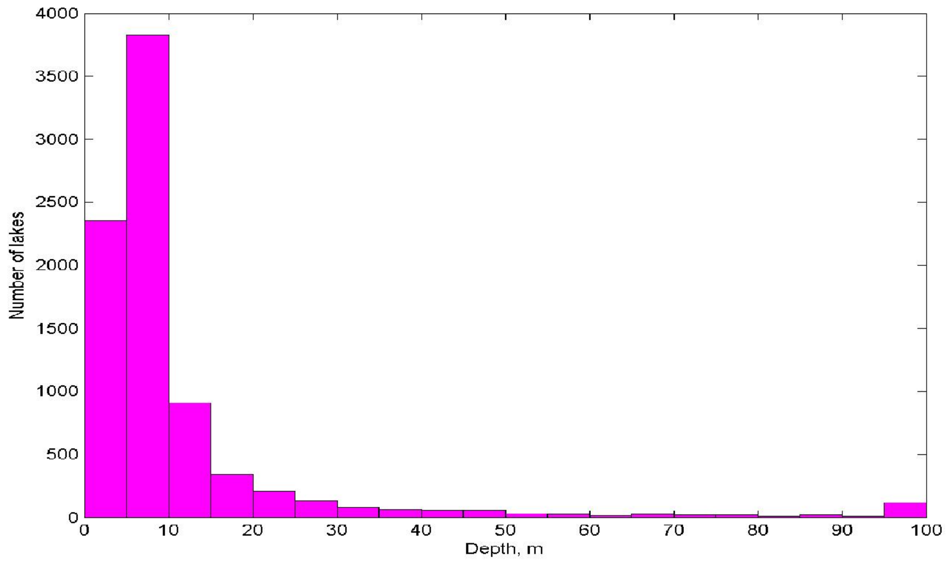
What to do with this?

$$H_{crit} = C_1 h_{SECCHI} + \sqrt{{C_1}^2 {h_{SECCHI}}^2 + C_2 L L_{MO}}$$

- Climate modeling and NWP:

avoiding vertical resolution for the majority of lakes in global models

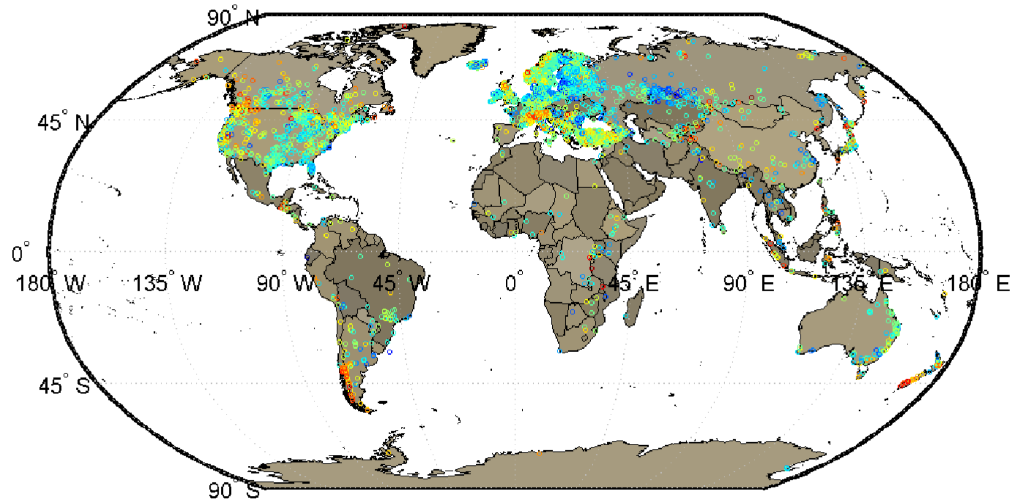
- Upscaling lakes in biogeochemical models

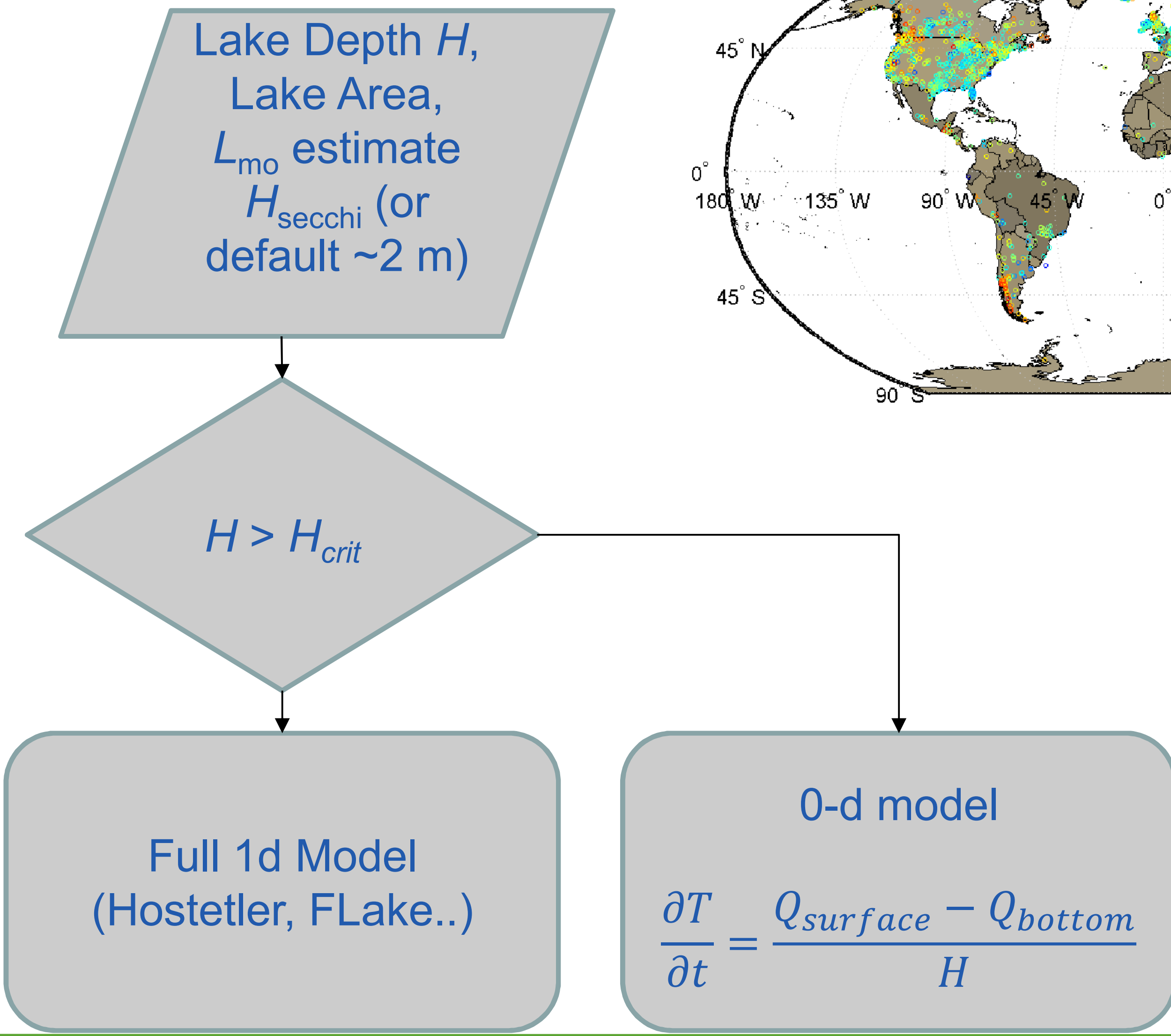


~47% of lakes in the lake depth database are shallower than 10m

What to do with this?

$$H_{crit} = C_1 h_{SECCHI} + \sqrt{C_1^{\,2} h_{SECCHI}^{\,2} + C_2 L L_{MO}}$$





Acknowledgements

Funding: German Science Foundation (DFG)

Data: IGB, AWI, National Centers for Environmental Prediction (NCEP), National Center for Atmospheric Research (NCAR), Maine Volunteer Lake Monitoring Program, International Lake Environment Committee Foundation

Sampling: Thomas Hintze, Bernd Schütze, Reinhard Hölzel, Helgard Täuscher, Ursula Newen

Discussions: Alena Gsell, Deniz Özkundakci, Ulrike Scharfenberger, Silke R. Schmidt, Torsten Seltmann

Institutions: Smithsonian Environmental Research Center (SERC)

Thank you for listening

Further reading:

Kirillin, G., and T. Shatwell. "Generalized scaling of seasonal thermal stratification in lakes." *Earth-Science Reviews* 161 (2016): 179-190.

Leibniz-Institute of Freshwater Ecology and Inland Fisheries

Smithsonian Environmental Research Center

Deutsche Forschungsgemeinschaft